U–Pb zircon geochronology, petrochemical and Sr–Nd isotopic characteristic of Late Neoproterozoic granitoids of the Bornaward complex (Bardaskan-NE Iran)

Abstract:

The Bornaward granitoids in the Taknar zone are located in the northeast of the central Iranian block in northeast Iran (Khorasan Razavi province), about 280 km southwest of Mashhad city and 28 km northwest of Bardaskan city. Taknar zone is an exotic block, bordered by two major faults, the Great Kavir fault in the south and Rivash fault in the north. Intrusive rocks of the study area, called the Bornaward granitoid complex (BGC), include of granite, alkali granite, syenogranite, leucogranite, granophyre, monzogranite, granodiorite, tonalite, diorite and gabbro intruded into the center of Taknar zone. These intrusive rocks affected low grade metamorphism.

The results of U-Pb zircon dating on two granite samples, one belonging to the Taknar mine west of the study area and the other from the Bornaward granitoids in the eastern part of study area, and also one granodiorite from the Taknar mine area and one diorite from the Bornaward area, yield ages of the granites as 540.5±2.9 Ma (Taknar mine area) and 550.41+3.21,-4.54 Ma (Bornaward area), the granodiorite as 550±6.9 Ma and diorite as 551.96±4.32 Ma, all Late Neoproterozoic.

The Bornaward intrusive bodies are classified as belonging to the ilmenite-series of reduced granitoids. Some small high magnetite-granite and tonalite outcrops in the study area are classified as belonging to the magnetite-series of oxidized granitoids.

Chemically, most granitoids of the study area are S-type middle-high metaluminous to slightly-middle peraluminous and belong to tholeiite, calc-alkaline to high-K calc-alkaline rock series with enrichments in LIL (Cs, Rb and Ba, U, K, Zr, Y, Th) elements and depletion in HIL (Sr and Nb, Ta, Ti) elements. Chondrite-normalized Rare Earth Elements (REEs) plots indicate minor enrichments of LREEs in comparison with HREEs, with $(La/Yb)_N$ between 1.04 -7.90 and total of REEs of the samples between 44.8 ppm (minimum) and 293.5 ppm (maximum) with strong negative anomaly of Eu compared to other Rare Earth elements.

The Bornaward granitoid have an initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ranging from 0.703514 to 0.716888 and 0.511585 to 0.512061, respectively, when recalculated to an age of 550 to 538 Ma, consistent with the new radiometric age results. Initial εNd isotope values for granite, granodiorite and diorite range from -6.73 to 2.52. T_{DM} age of the BGC is 1.08-1.70 Ga. This indicates that the Bornaward granitoid complex (BGC) derived from partial melting of distinct basement source regions with very high initial $^{87}Sr/^{86}Sr$ and underwent extensive crustal contamination.
Keywords: Taknar, Bornaward, U-Pb dating, Zircon, Sr-Nd, Late Neoproterozoic

Materials and methods:

Major oxides containing SiO_2, Al_2O_3, Na_2O, MgO, K_2O, TiO_2, MnO, CaO, P_2O_5, Fe_2O_3 and L.O.I were measured by X-ray fluorescence spectrometry (XRF) method in the Analytical Geology Lab. of spectrum Kansaran Binaloud in Iran. Trace elements containing Ba, Be, Co, Cs, Ga, Hf, Nb, Rb, Sn, Sr, Ta, Th, U, V, W, Zr, Y and REEs of rocks was determined by Induced Couple Mass Spectrometer (ICP-MS) in Acme Analytical Laboratories (Vancouver, Canada). Detection limit of trace elements and REEs in the research is between 0.01 to 8 ppm.

Four rock samples containing granite, granodiorite and diorite were chosen for zircon U-Pb age dating. The zircons analyzed in this study were separated, using standard heavy liquid (Bromoform) and magnetic procedures. From each rock about 50 zircon grains were separated. Zircons were mounted along with a zircon standard and a couple of chips of NBS 610 Trace Element Glass in epoxy and polished down to 20 µm. Zircon age dating was done at the Arizona Laser Chron Center. U–Pb isotope data were collected by using a New Wave 193 nm ArF laser ablation system coupled to a Nu Plasma HR inductively coupled plasma-mass spectrometer (ICP-MS) at the Arizona Laserchron Center according to methods described by Gehrels et al. (2008).

All of the zircons were examined using a combination of Cathodoluminescence (CL) and optical microscopy prior to analysis. Cathodoluminescence images are acquired for samples to be analyzed because they provide a powerful tool for placing laser pits in homogeneous portions of crystals, and also can help determine the origin (e.g., igneous, metamorphic, hydrothermal) of zircon grains. Laser ablation takes place with a beam diameter of either 35 or 25 microns for most applications, or with a beam diameter of 15 or 10 microns if finer spatial resolution is needed.

Sr and Nd isotopic compositions for other four whole rock samples (BkCh-06, BkCh-08 BkCh-14 and BkCh-15) were determined at the Laboratório de Geologia Isotópica da Universidade de Aveiro, Portugal. The selected powdered samples were dissolved with HF/HNO_3 in Teflon Parr acid digestion bombs at 200ºC for 3 days. After evaporation of the final solution, the samples were dissolved with HCl (6N) and dried. The target elements were purified using conventional ion chromatography technique in two stages: (i) separation of Sr and REE elements in ion exchange column with AG8 50W Bio-Rad cation exchange resin; (ii) purification of Nd from other lanthanides elements in columns with Ln Resin (ElChrom Technologies) cation exchange resin. All reagents used in the preparation of the samples were sub-boiling distilled, and the water produced by a Milli-Q Element (Millipore) apparatus. Sr was loaded on a single Ta filament with H_3PO_4, whereas Nd was loaded on a Ta outer side filament with HCl in a triple filament arrangement.

Geology:

The present study is concerned with granitoid occurrences in the northeastern part of the Central Iranian Plate (CIP) in an area named “Taknar zone”. The Taknar Inlier near Kashmar, Khorasan province (NE-Iran), consists of an uplifted portion of the central Iranian Precambrian to Paleozoic basement and its Mesozoic-Cenozoic cover (Fig.1). To the south it is bordered by the Great Kavir Fault (Darouneh Fault), to the north by the Taknar Fault. Both these fault systems coincide west of the Inlier (Muller & Walter, 1983). The Taknar Fault might represent a major dextral strike-slip fault, which bounds the Taknar uplift to the north against the Sabzevar zone, dominated by oceanic Mesozoic and Cenozoic rock successions. Along the still recently active sinistral strike-slip fault of the Great Kavir System the Taknar uplift is in direct contact with the northern part of the Lut Block. The Taknar uplift is suggested to originally represent a marginal segment of the continental Central and East Iranian microplate and part of Sabzevar zone.

1. Petrography of Bornaward granitoid

The early magmatic episode in the Bornaward area is characterized by the occurrence of gabbro and diorite. After this, tonalite and granodiorite intruded into basic rocks. Granite represents the late stage intrusive episode which occurs extensively in the Bornaward area.

1-1. Gabbro

The gabbros have intergranular, hypidiomorphic granular and ophitic textures. The rock is composed of 40-45 vol.% clinopyroxene with simply-twinned, yellowish orange in color, 46-52 vol.% plagioclase as euhedral crystals, 5-7 vol.% brown hornblende and 1-3 vol.% opaque minerals. Most of plagioclases are fresh to low altered to sericite and epidote. Other alteration minerals are tremolite, actinolite and chlorite. Accessory minerals include Fe-Ti oxide and apatite. The margin of bodies is more fine grain than center, because of fast cooling, therefore, has formed microgabbro.

1-2. Diorite

The textures of these rocks include hypidiomorphic granular, allotriomorphic granular and slightly porphyritic. The rock contain coarse grains including of 35-39 vol.% plagioclase, 30-36 vol.% green hornblende, 2-4 vol.% quartz in groundmass and as phenocryst and anhedral with wavy silence. Plagioclases usually have normal zoning and highly altered to sericite. Other alteration minerals include epidote, zoisite and clinozoisite. Accessory minerals contain zircon, apatite, magnetite, rutile, zircon and Fe-Ti oxides.

1-3- Monzogranite

Mineralogy of the unit contain of 18-25 vol.% fine to coarse anhedral quartz grains in the groundmass and as phenocryst and show undulse extinction, recrystallization, ridged margins and subgrains. These cases are reasons for effect of tectonic deformation. Other mineral is plagioclase (28-35 vol.%) generally shown to effects sericitization and formed as phenocryst and in background rock and 30-38 vol.% K-feldspar (orthoclase and microcline) as phenocryst and in the groundmass forming pertitic texture.

1-4. Tonalite

The tonalite has granular and micro-pertitic textures. The mineralogy of rock contains 36-40 vol.% euhedral to subhedral plagioclase (oligoclase or andesine) minerals with size up to 4 mm long and normal compositional zoning, 25-33 vol.% subhedral amphibole grains, 15-24 vol.% quartz, 5-7 vol.% biotite, and 4-6 vol.% K-feldspar. Accessory minerals include apatite, sphen, zircon and magnetite. Alteration minerals include chlorite, epidote, zoisite, sericite, kaolinite and opaque minerals.

1-5. Granodiorite

The textures of these rocks include hypidiomorphic granular, micro-pertitic and sometimes microgranophyric, porphyritic and graphic intergrowth. This rock contain 18-26 vol.% anhedral quartz grains to wavy silence, recrystallization, ridged margins and subgrains that this is reasons for effect of dynamic metamorphism. Other minerals contain 16-24 vol.% K-feldspar (orthoclase and microcline with micro-pertitic texture) in the groundmass and as phenocryst, plagioclases usually have normal compositional zoning and an average 45 vol.% (ranging from 36% to 58%) with polysynthetic and pericline twins, 10 vol.% green and brown fine grain biotite between quartz and plagioclase grains, 4-9 vol.% green hornblende. Accessory minerals are sphene, zircon, and apatite appendixed in biotite, ilmenite and magnetite.

1-6. Granite

Majority of the rocks have micrographic, micro-pertite, granophyric, idiomorphic granular, hypidiomorphic granular, granular and slightly porphyritic textures. On the basis of microscopic study, the rock is composed of 33-35 vol.% fine to coarse quartz in the groundmass and into alkali-feldspar and majority of quartz grains are anhedral and show undulse extinction, recrystallization, ridged margins and subgrains. These cases are reasons for effect of tectonic deformation. In the rock, plagioclase shows strong resorption along margins and only small anhedral plagioclase grains occur in some samples. Other minerals contain 24-29 vol.% K-feldspar (orthoclase and microcline) as phenocryst and in the groundmass forming granophyric texture, 20-27 vol.% plagioclase with polysynthetic and pericline twins and oscillatory zoning, and 8 vol.% green and brown fine grain biotite. Accessory minerals include magnetite, ilmenite, zircon, sphene, epidote, zoisite and clinozoisite.

2. Geochemical analysis results

2-1. Major and trace elements geochemistry

The Bornaward-Taknar granitoids have a wide range of chemical compositions, with SiO_2= 65.03-77.02%, Al_2O_3=10.93-13.66%, MgO=0.01-2.27%, FeO=1.01–10.35% (based on total Fe), CaO=0.21-4.37%. They are relatively high in total alkalis, with K_2O=0.55–5.83% and Na_2O=0.28–7.02%, and the total K_2O+Na_2O ranging from 4.76% to 8.70%, and low abundances of MnO, P_2O_5 and TiO_2. Representative rocks of the Bornaward granitoid complex (BGC) were analyzed for major, trace elements and rare earth elements. Chemical composition of Bornaward granitoid rocks were plotted in TAS diagram, and they fall into the fields of granite, granodiorite and tonalite. BGC rocks locate in middle-high metaluminous to slightly-middle peraluminous groups and their alumina-saturation index (ASI: molar $Al_2O_3/CaO+Na_2O+K_2O$)=0.70-1.82) (Chappell and White, 2001). Mineral assemblages of some of the intrusive rocks (biotite, hornblende, and magnetite) support an interpretation that they belong to the magnetite-series of oxidized granitoids and also, mineral assemblages of other intrusive rocks (biotite and ilmenite) support an interpretation that they belong to the ilmenite-series of oxidized granitoids (S-type granitoids). So, based on SiO_2- K_2O diagram (Peccerilo and Taylor, 1976) (Fig.2). BGC belong to Tholeiite, Calc-alkaline and High K calc-alkaline series. Chemical composition of Bornaward granitoid rocks are plotted in 10000×Ga/Al vs. trace element (Nb) and major oxides (Na_2O+K_2O) discrimination diagrams. They plot in the field of I & S-type granites (Whalen et al., 1987) (Fig. 3).

In the lower continental crust normalized trace element diagram indicates that BGC intrusive rocks are relatively enriched in large ion lithophile elements (LILE: Cs, Rb, Ba, K, La, Nd, Hf, Zr and Y) and other incompatible elements that behave very similarly to LILE (Th and U), and strongly depleted in high field strength elements (HFSE: Nb, Ta, Sr and Ti). Bornaward granitoids show very strong depletion in Sr and Ti, and very enrichment in U, Y and specially Hf and Zr.

According to the data related to Bornaward intrusive rocks major and trace elements in the primitive-mantle-normalized trace element spider diagram (Sun and McDonough, 1989), Sr, Ba and Ti are roughly compatible, and their concentrations decrease sharply in a linear array during the evolution of magma. Sr/Ba ratios only slightly decrease, whereas the Rb/Sr ratios exhibit a strong increase from the low- to the high-silica members in each granitoid suite. On the basis of the primitive mantle-normalized element pattern the Bornaward intrusive rocks is distinguished by the enrichment of LILE (K, Cs, Rb, Ba) and the low HFSE content (V, Cr, Co, Ni, Cu). Also, the negative Nb anomaly is very significant, specially the granites. Negative Sr and Eu anomalies can be explained by plagioclase fractionation.

The Bornaward HREE pattern is relatively flat. The Bornaward granitoid Eu anomalies exhibits a significant negative Eu anomaly within a moderately fractioned LREE pattern with $(La/Lu)_N$=1.07-9.23, $(La/Sm)_N$=1.25-4 and $(Gd/Lu)_N$=0.4-1.08, only one of the high magnetite-bearing granite have flat Eu anomaly, because of the low abundance or lack of plagioclase in the residue. The Sr and Eu negative anomalies can be explained by plagioclase fractionation, whereas the other negative anomalies appear to be inherited from the petrogenetic process. The overall REE abundances of the granitoids of Bornaward area coincide with typical crustal derived granitoids (i.e. La is 20-200 times chondrite, Yb is 8-50 times chondrite), as reported by Holtz (1989) and Williamson et al. (1996).

3. U-Th-Pb Zircon age dating

The calculated isotopic age for sample BKth-1 granite tend to plot along a well-defined discordia line on the concordia plot (Fig.4), with a regressed upper intercept mean age value of 550.41 +3.21, -4.54 Ma. The calculated isotopic age for sample BKTh-3 diorite is presented show the mean age value of 551.96±4.32 Ma (Fig.5). The results of calculation of isotopic sample TAK2-8, based on 12 analyzed points the mean age value for granite is 550±6.9 Ma The calculated isotopic age for sample TAK1-5 granodiorite based on 32 analyzed points show the mean age value for granodiorite is 540.5±2.9 Ma (Figs.6,7).

The relatively invariable U/Th ratios and their respective spot U-Pb ages are consistent with magmatic zircons, and no inherited components were detected. These characteristics together with the high closure temperatures of zircon allow us to interpret the U-Pb data as representation of the crystallization ages of the igneous protolith (s) of the Bornaward granitoid complex (BGC). Therefore, the U-Th-Pb zircon dating indicate, that all four samples intruded in the Precambrian (Ediacaran) time.

4. Sr–Nd isotopes

Sr and Nd isotope data have a range in $(^{87}Sr/^{86}Sr)_i$ and $(^{143}Nd/^{144}Nd)_i$ from 0.703514 to 0.716888 and 0.511791 to 0.512061, respectively, when recalculated to an age of 553 and 538 Ma, they are consistent with the new radiometric results. Initial εNd isotope values for granite, granodiorite, monzogranite and diorite range from -6.73 to 2.52.

Discussion:

5. Source of magma and tectonic setting of Bornaward granitoid

Chemically BGC rocks locate in middle-high metaluminous to slightly-middle peraluminous groups (A/CNK= 0.70-1.82). Also, based on SiO_2-K_2O diagram (Peccerilo and Taylor, 1976), the BGC rocks belong to tholeiite, Calc-alkaline and High K-calc-alkaline series. The variations in major and trace elements of the BGC rocks show the normal partial crystallization trend of hornblende, biotite, plagioclase and titano-magnetite, and the accumulation of incompatible elements in the rest of magma.

The middle-high metaluminous characteristics for the intrusive rocks show that the Bornaward granitoid plot in the field of the volcanic arc granites in the diagrams proposed by Pearce et al. (1984). Location of some of the Bornaward intrusive rocks in WPG and ORG fields is because of intense alteration and tectonic effects on the rocks after magmatism. Also, low Nb/Y ratio is characteristic of magmatic arc related to subduction zones (Pearce, 1983).

Compositions of granitic rocks from the Bornaward plotted on the CaO/Na_2O– Al_2O_3/TiO_2 diagram (Fig.8). The field of S-type granitoids and its boundaries separate from other granitoids (Sylvester, 1998). The BGC rocks that have low SiO_2 (<71 wt.%) have high FeOt+MgO+TiO_2 (>4 wt.%) and high CaO/Na_2O ratios, but granitoids with high SiO_2 (> 71 wt.%) have low FeOt+MgO+TiO_2 (< 4 wt.%) and low CaO/Na_2O ratios. These relationships are consistent with the low CaO/Na_2O S-granites having pelitic sources and high CaO/Na_2O S-granites having psammitic sources (Sylvester, 1998).

The Rb/Sr vs. Rb/Ba discrimination diagram shows the Bornaward granitoid bodies plot next to meta-psammite and meta-greywacke derived melt (Fig.8). Psammite-derived melts will tend to have higher Rb/Sr and Rb/Ba than their sources. In general, the melt produced at low melting fractions is indistinguishable (mainly metaluminous), irrespective of the nature of the protolith. Metaluminous meta-igneous rocks are able to produce peraluminous felsic melts at low melting fractions and in water-deficient conditions. As the melting increases, primary component of the source rocks are progressively incorporated in the melt. The Ti and Mg content of biotite directly control the reaction temperature interval in biotite. As these elements increase in biotite, the reaction temperature interval will expand (Sylvester, 1998; Karimpour, 2010).

Large amounts of plagioclase will be left behind after psammite melting. Because Sr and Ba are compatible in plagioclase, whereas Rb is incompatible (e.g., Harris and Inger, 1992), psammite-derived melts will tend to have higher Rb/Sr and Rb/Ba than their sources. Thus, Rb/Sr and Rb/Ba of S-type granite melts is a function not only of source composition but also the amounts of plagioclase and K-feldspar left behind in the source region. Psammitic rocks, particularly meta-greywackes, are widespread at convergent plate margins and are thus likely to have been available for anatexis in many crustal blocks accreted in collisional zones (Vielzeuf and Montel, 1994). The predominance of pelite or psammite sources of S- granites in a particular collision belt may reflect the maturity of the accreted crustal blocks, with psammite sources pointing to immature plate margin (island- and continental-arc) successions.

Initial $^{87}Sr/^{86}Sr$ isotope values for the Bornaward intrusive rocks range from 0.691002 to 0.716888 and MORB is less than 0.7040. The lowest initial $^{87}Sr/^{86}Sr$ ratios calculated in the Bornaward samples seem to be anomalous, which could be explained by: 1) either samples with very low $^{87}Sr/^{86}Sr$ ratios for a Neoproterozoic age were collected in actually younger plutonic bodies; 2) or the anomalously low $^{87}Sr/^{86}Sr$ initial ratio is an artifact from the magnification of the error in the calculation, due to the conjunction of high $^{87}Rb/^{86}Sr$ values with an old age. Since, in one hand, the lowest initial $^{87}Sr/^{86}Sr$ values were obtained in samples with high $^{87}Rb/^{86}Sr$ and, in the other hand, there is no evidence for younger ages in those samples, the second hypothesis seems to be the most likely. Initial $^{143}Nd/^{144}Nd$ isotope values for the Bornaward intrusive rocks range from 0.511585 to 0.512061 and for MORB is between 0.5130 to 0.5135. This indicates the source of magma for the Bornaward granitoid was originated from: 1) the tholeiitic magmatism with due attention to the isotope values of the samples of granite (BKCh-14), granite (BKTh-1), diorite (BKTh-3), granite (BKCh-06), granite (BKCh-08) and monzogranite (BKCh-15) in the Bornaward district (the east of study area) in near of subduction zone, and 2) Calc alkaline to high K-calc alkaline magmatism and contamination to continental crust (Taknar district) and more radiogenic with due attention to the isotope values of the samples of granodiorite (TK2-8) and granite (TK1-5) in the Taknar district (the west of study area) in distal of subduction zone to form of S-type granitoids.

The Bornaward intrusive rocks yields a T_{DM} age of 1.08-1.70 Ga. This indicates that the intrusive rocks being derived from both source: 1) the tholeiitic magmatism and 2) partial melting of distinct basement source regions. Also, the initial εNd values suggest that the Bornaward intrusive rocks belong to Taknar district are not compatible with a mid-ocean ridge basaltic (MORB) origin. The values of initial εNd suggest that the intrusive rocks of Taknar district originated from a depleted mantle. In the Nd–Sr isotope diagram, all of the Bornaward intrusive rocks show a negative correlation between the Nd and Sr ratios, and also showed mixing of the MORB source and recycled (subducted) sediments (Fig.9).

The initial $^{87}Sr/^{86}Sr$ isotope values of the BKCh-14, BKTh-1, BKTh-3, BKCh-06 and BKCh-08 in the Bornaward district (0.691002 to 0.709215) is different from the value shown by the slate (0.719306). This difference indicates that although the source of magma was in continental crust, the source was not solely the slate-related rock types. Whereas, the initial $^{87}Sr/^{86}Sr$ isotope values of the TK2-8 and TK1-5 in the Taknar district (0.713566 and 0.716888) is near to slate.

6. Regional implications of the Late Neoproterozoic orogeny and granitoid rocks in Iran

The 548 to 526 Ma orogeny in central Iran brings about significant paleotectonic implications, in the context of the Arabia-Iran-India paleogeographic continuity. If the late Neoproterozoic-Early Cambrian events in central Iran were associated with the establishment of a continental-margin (Andean-type) magmatic arc, the adjoining Arabian and Indian (Proto-Tethyan) margins of the Gondwanaland must have experienced a comparable set of events. The verification of this hypothesis is an arduous task, mainly because of the complex Phanerozoic history of the above margins. The Proto-Tethyan margin of India has been intensely affected by the Cenozoic Himalayan Orogeny, whereas the ancient rocks of the Arabian margin are buried under the thick sedimentary piles of the Arabian Platform and the Zagros Basin. In the following discussion we attempt to demonstrate, based on available geologic and age data, the evidence for concurrent orogenic activity in various Gondwana segments of the Proto-Tethys margin (Ramezani and Tucker, 2003).

Results of study by Hassanzadeh (2008) demonstrate that Late Neoproterozoic to Early Cambrian granitoids and granitic gneisses are present in all continental structural zones of Iran north of the Zagros, from the Sanandaj–Sirjan zone to the northern margin of the Alborz Mountains. Therefore, the crystalline basement of Iran can be considered to be the approximate northern continuation of the Arabian platform. Since definitive crust of comparable age is generally absent in cratonic Eurasia (Veevers, 2003), the occurrences of granitoids with Neoproterozoic ages from the Zagros to the northern foothills of the Alborz point to a Gondwana affinity for the continental terrains composing Iran.

The Bornaward granitoid complex (BGC) rocks of exposed in eastern-north of central Iran have Late Neoproterozoic age. Distribution of Late Neoproterozoic igneous plutons in Iran ranging in age from 599 to 544 Ma which are widespread across central Iran and the Sanandaj–Sirjan structural zone.

Results:

On the basis of U-Th-Pb zircon geochronology, the oldest of Iran granitoid bodies have formed between older metamorphosed rocks in the late Neoproterozoic-Cambrian. The most of late Neoproterozoic (Precambrian) granitoids have located in the Central Iranian block. The Bornaward granitoid complex (BGC) is the oldest magmatic intrusions exposed in the Taknar zone belonged to the Central Iranian Block and represent the elements of a terminal late Neoproterozoic-Early Cambrian magmatic arc complex. This complex belonged to a greater late Neoproterozoic-early Paleozoic orogenic system that was active along the Proto-Tethyan margin of the Gondwanaland supercontinent. The intrusive rocks are composed of granite, granophyre, leucogranite, granodiorite, tonalite, monzogranite, diorite and gabbro. Granite, granodiorite and diorite rocks are dominant in the study area.

Chemically, the Bornaward intrusive rocks are middle-high metaluminous to low-middle peraluminous and belonged to Tholeiite, Calc-alkaline to high-K calc-alkaline series with enrichment in LILE= Cs, Rb and Ba, K, Zr, Y, Th, U, La and Hf elements and depletion in HILE= Sr and Nb, Ta, Ti elements. On the basis of K_2O enrichment of the intrusive rocks belong to high- K calc alkaline series and a clear enrichment in large-ion lithophile elements (LILE) coupled with high-field-strength elements (HFSE) depletion, with Nb, Ta and Ti negative anomalies, typical is related to subduction zone magma.

The results of U-Pb zircon age of two granites (BKTh-1 and TK2-8 samples) is 550.41 +3.21, -4.54 and 540.5±2.9 Ma, respectively. Also, the U-Pb zircon age of granodiorite (TK1-5 sample) and diorite (BKTh-3 sample) is 550.6±6.9 and 551.96±4.32, respectively. The ages of these rocks belong to Precambrian (late Neoproterozoic time). So, the Bornaward diorite is older than granite and granodiorite. Occurrences of diorite and gabbro locate in the center Bornaward granitoid complex as reversed zoning.

The Bornaward granitoid have a initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ranging from 0.691002 to 0.716888 and 0.511585 to 0.512601, respectively, Thus, the presence of mantle-derived melts showing high-K affinity together with typical calc-alkaline mafic melts is the most striking feature of Cambrian magmatism.

Initial εNd isotope values for granites, granodiorite, monzogranite and diorite range from -6.73 to 2.52. T_{DM} age of the BGC is 1.08-1.70 Ga. This indicates that the Bornaward granitoid complex (BGC) derived from two sources: 1) tholeiitic magmatism, and 2) Calc alkaline to high K-calc alkaline magmatism related to partial melting of distinct basement source regions with very high initial $^{87}Sr/^{86}Sr$ that undergo extensive crustal contamination.

On the basis of the chemically characteristics of Bornaward intrusive rocks which have low content of HFSE, enrichment in LILE and Th, and depletion in Nb and Ta, the source magma of Bornaward intrusive rocks belongs to subduction zone. The origin of these rocks is the active magmatic arc in Late Neoproterozoic – Cambrian (Ramezani and Tucker, 2003). The magmatic arc at the large scale was along margin of Proto-Tethyan and Gondwana. The Central Iran Block is one of the divided regions of this active margin that as unfixed parts including Central Iran block was located as Himalya-Alpe orogeny system.

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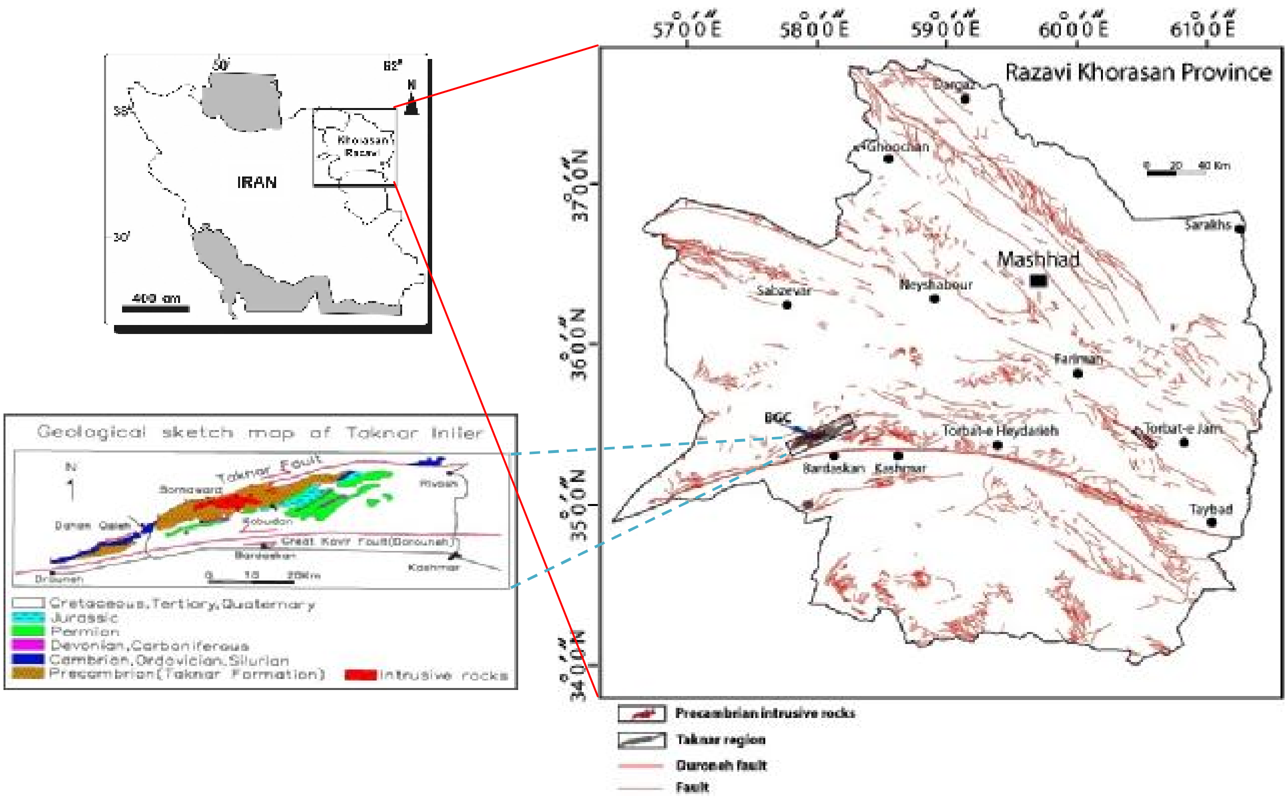
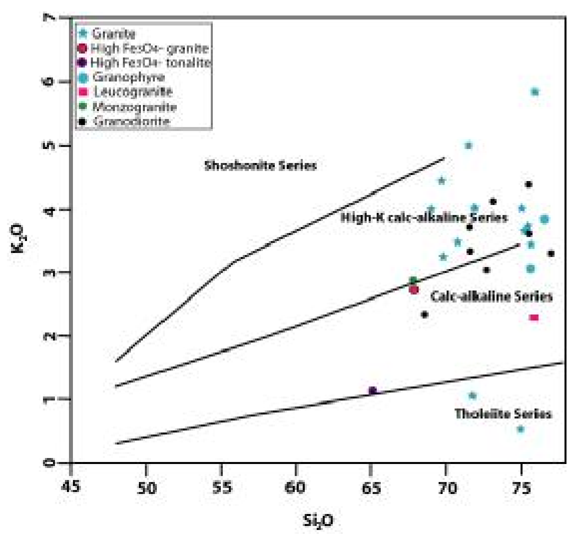


Fig 1. Location of Bornaward region and Precambrian intrusive rocks in NE Iran.



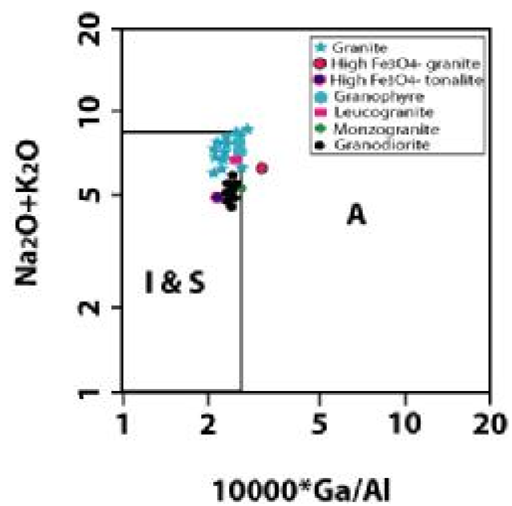
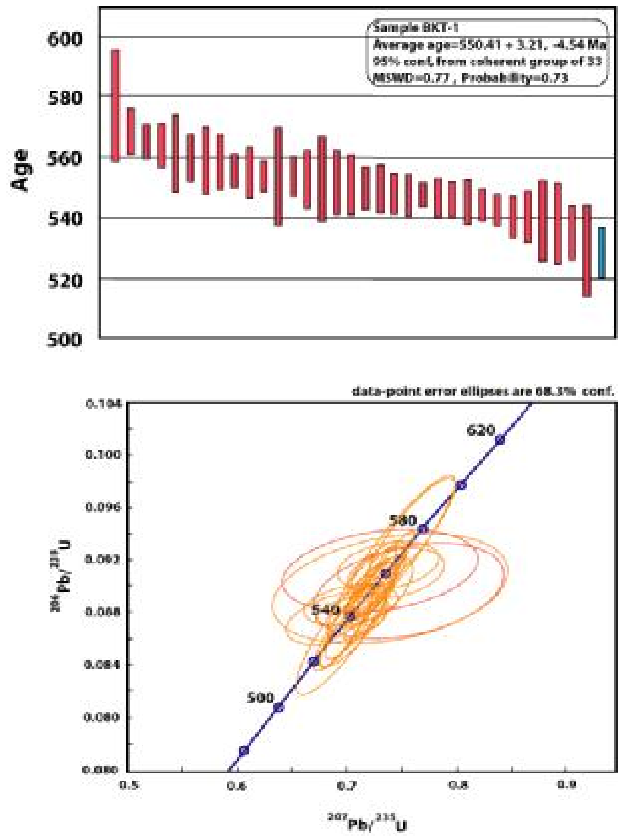


Fig. 2. K2O vs. SiO2 variation diagram with boundaries by for high-K, medium-K, and low-K magma series (Peccerilo and Taylor, 1976).

Fig. 3. Bornaward granitoid rocks are plotted in the field of I, S and A type (Whalen et al., 1987).



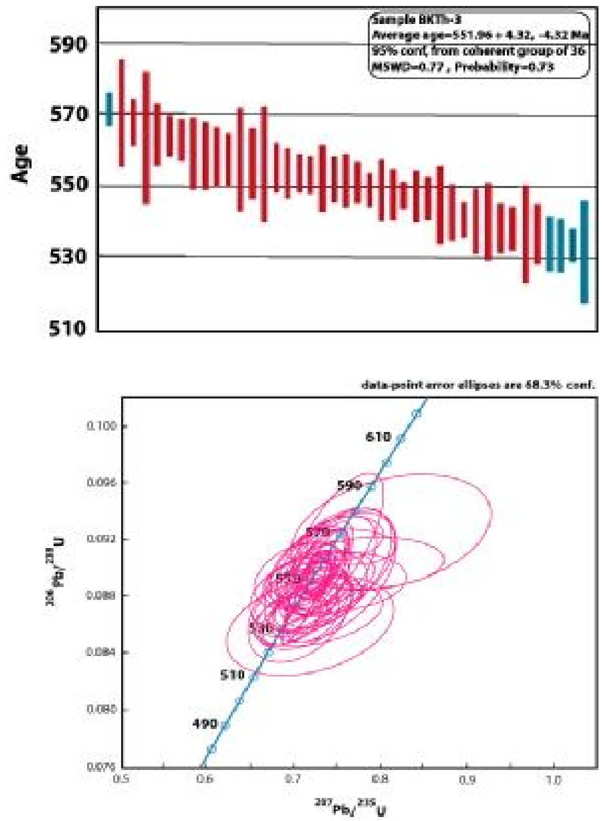
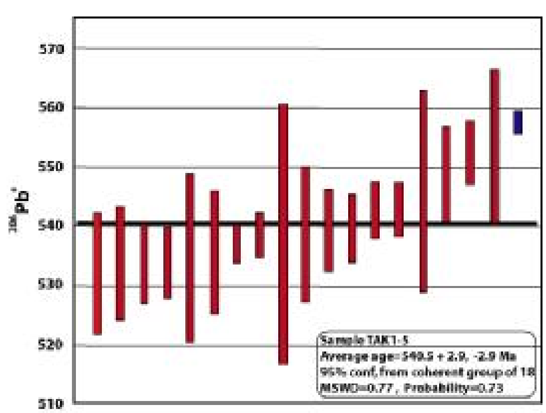


Fig. 4. Zircon U–Pb dating of Bornaward granite: (a) concordia diagram, Concordia and (b) average age plot.

Fig. 5. Zircon U–Pb dating of Bornaward diorite: (a) diagram and (b) average age plot.



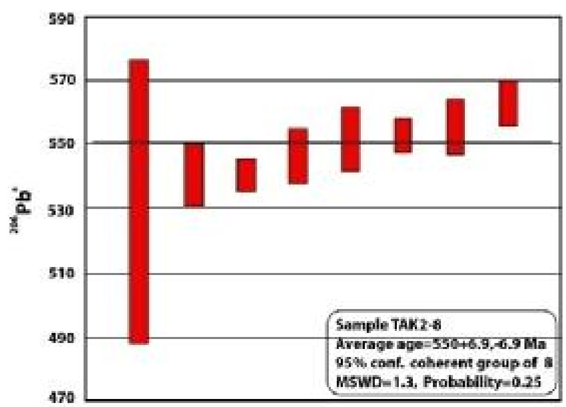


Fig. 6. TuffZirc graphics calculating the age of zircons of Taknar granite (TAK1-5)-(Left).

Fig. 7. TuffZirc graphics for calculating the age of zircons of Taknar granodiorite (TAK2-8)-(Right).

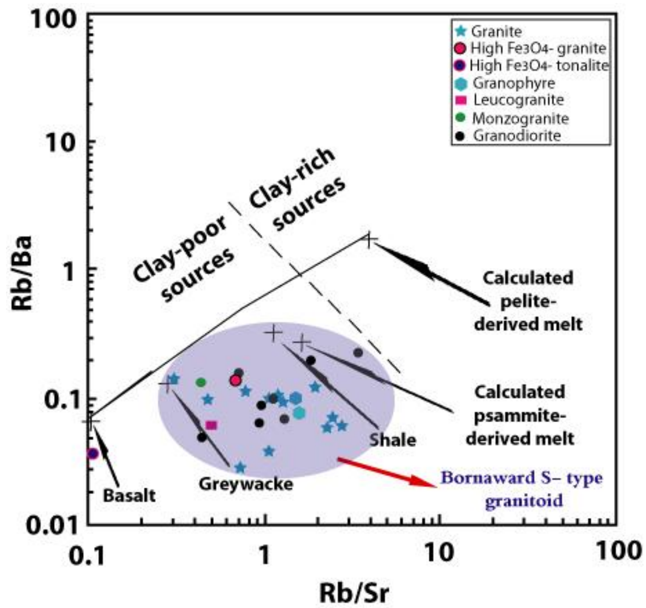


Fig.8. Plot of Rb/Sr vs. Rb/Ba, The melt of Bornaward S-type granitoids derived psammite and greywacke rocks.

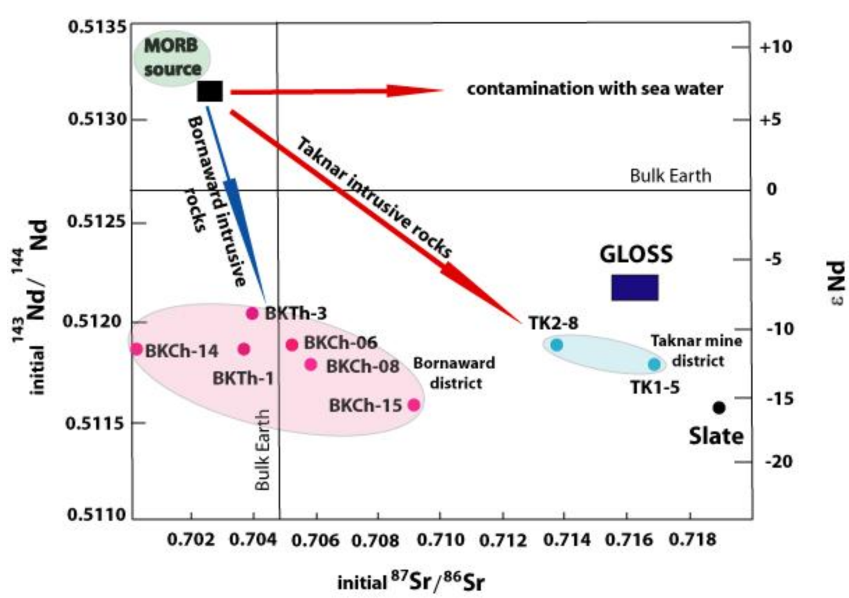


Fig. 9. A $^{143}Nd/^{144}Nd$–$^{87}Sr/^{86}Sr$ diagram for the Bornaward intrusive rocks for T = 0Ma. This shows that the change in 87Sr/86Sr ratios is not related to an alteration caused by seawater, and further implies a mixing of source magma with subduction sediments (Rollinson, 2007), since seawater would not significantly change the Nd-isotope ratio. The trend seen in the metabasites is similar to the volcanic rocks island arc and infers the mixing of source magma with slab sediments. GLOSS is the average composition of global subducting sediment from Plank and Langmuir (1998).